ELECTROSTATICALLY DRIVEN MICRO-HYDRAULIC ACTUATOR ARRAYS

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ABSTRACT

This paper describes an all-electrical individually-addressable micro-hydraulic actuator array that produces high displacement and force by utilizing hydraulic amplification and electrostatic control, offering a considerable improvement in fabrication technique and performance over the recently-introduced micro-piston hydraulic actuator array [1,2]. The fabricated micro system consists of 3×3 and 4×4 arrays of actuator cells. A curved electrode capacitive actuator with a diameter of 2236 μm driven at 200 V produces 30.0 μm deflection on the front side at 14.4 kPa of pressure which corresponds to 11.3 mN force generated by the capacitive actuator on the back side. Actuation occurs from DC to 15 Hz.

INTRODUCTION

High-force, large-deflection actuators are critical for devices such as valves and pumps used in microfluidic systems, for surface bump manipulation in tactile displays, and micro-airfoil control. Table 1 lists potential actuation methods.

Table 1: Comparison of several actuation methods.

	E.S.	Hydra.	Piezo.	Pneu.	E.M.
Force	Low	High	High	High	High
Deflection	Small	Large	Small	Large	Large
Fabrication & Materials	Easy	Difficult	Difficult	Difficult	Difficult
Power	Low	High	Low	High	High
Control	Easy	Easy	Medium	Easy	Hard
Speed	Fast	Medium	Fast	Slow	Fast

* E.S.=electrostatic; Hydra=hydraulic; Piezo=piezoelectric; Pneu= Pneumatic; E.M.=electro-magnetic

Electrostatic actuation cannot provide the high forces (~10-100 mN) required for many applications. Techniques capable of high force suffer from control difficulties (E.M.) or are limited to small deflections (Piezo.). This raises a need for a new class of actuators that offers controllable and high force actuation which can be delivered across a large displacement range. Our approach is to assist electrostatic actuation with hydraulic amplification. The E.S. mechanism allows for low power actuation and excellent control, while the hydraulic system provides large deflection and high force actuation.

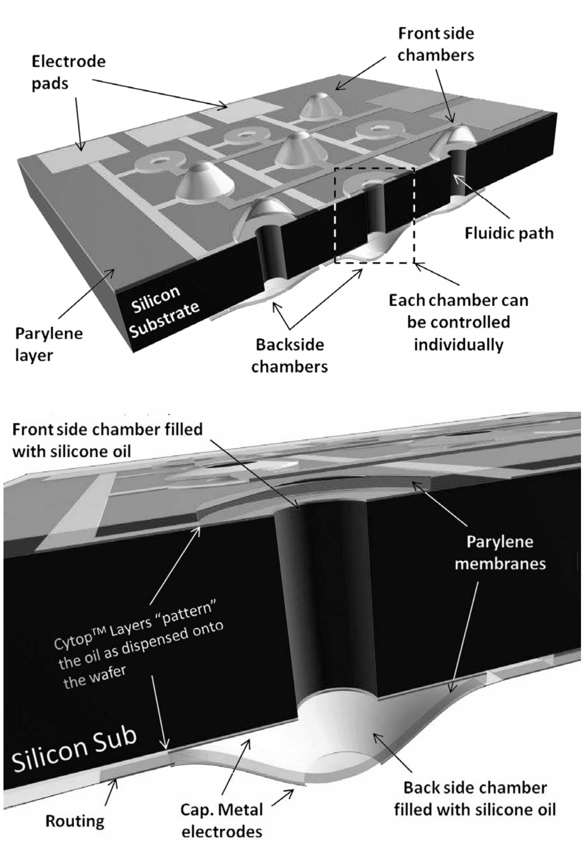

Figure 1: Schematic drawing of an array of micro-hydraulic cells made using direct deposition of Parylene over silicone fluid. The bottom sketch shows a close up of one of the cells.

The concept of a new technology which combines electrostatic and micro-hydraulic actuation to obtain large-force, large deflection, and low-power actuation is shown in Figure 1. This technology is referred to as electrostatic micro-hydraulic actuation or EMA. Each actuator cell consists of two Parylene membranes that cap two chambers on opposite sides of a wafer. The top and bottom chambers are connected with a channel etched through the wafer. Capacitive metal electrodes on the silicon surface and membrane allow electrostatic actuation (or sensing) on the back and/or front of the wafer. EMA is able to produce higher displacement and larger force than typical electrostatic actuators by filling the chambers and wafer-through channel with a non-conducting liquid which acts both as a hydraulic fluid and as the capacitor dielectric. As electrostatic actuation pulls down one flexible membrane, the liquid is pushed

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into the opposite chamber, causing its membrane to be deflected out of plane.

By varying the area of the front and back side chambers, amplification of either force or displacement is achievable. Furthermore, by carefully choosing the hydraulic liquid we can take advantage of its high dielectric constant to increase the electrostatic force (capacitance).

In previously published piston arrays, cross talk is inevitable due to use of a single large actuating chamber on one side of the wafer for actuating all of the cells in an array on the opposite side of the wafer, where the small membranes were latched whenever they were supposed to be at rest [1]. In that design, the single chamber provides fluidic connections between the cells during operation, causing cross-talk. In the new design presented here, each cell is actuated by its own membrane, minimizing cross talk between adjacent cells and eliminating the previously-required dual-side control electrodes. In addition, the wafer-level fabrication process and shift from piezoelectric to electrostatic actuation makes this architecture applicable to a variety of platforms.

For example, external pneumatic devices are widely used in fluidic devices, since they can provide high force and large displacement. The EMA design shown here can provide almost the same performance, but additionally can be integrated with other MEMS devices such as micro-fluidics on a single wafer if the proper sequence of fabrication steps is chosen.

FABRICATION PROCESS

The fabrication process is based on a wafer level technique for bubble-free encapsulation of a liquid dielectric that provides the option of having individual actuated chambers for each of the cells.

The chosen liquid dielectric material is polytrimethylsiloxane (Silicone oil 1,3,5-trimethyl-1,1,3,5,5-pentaphenyltrisiloxane) which has a vapor pressure at room temperature of under 1 mTorr, so that it can survive the low vacuum inside the Parylene deposition system [3]. After the oil is dispensed onto the wafer in the designated locations, the wafer is loaded in the Parylene deposition tool, and Parylene is deposited. The polymer conformally coats the oil on both sides of the wafer, encapsulating it [3]. Note that almost no leakage or evaporation of the liquid dielectric is expected during micro-system use since the silicone oil does not evaporate at atmospheric pressure and room temperature.

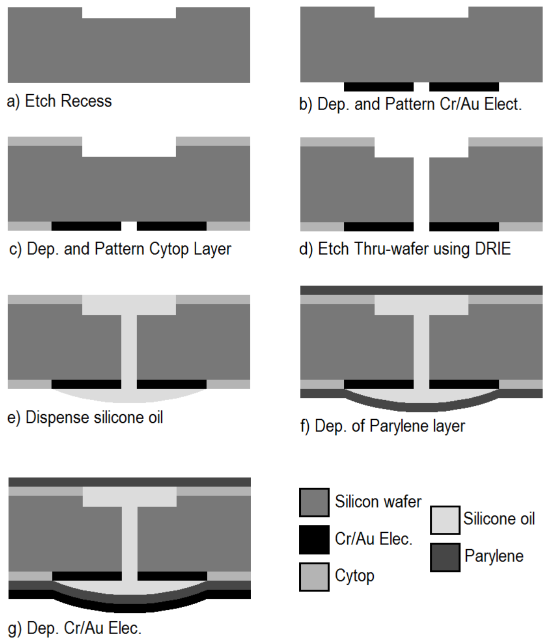

Figure 2: Fabrication process.

The fabrication process is shown in Figure 2. It begins with 3-4 μm dry etching of silicon to form a recess. This shallow recess plays an important role during liquid dispensing, as described later. Cr/Au electrodes are then deposited and patterned. Next, Cytop^{TM}, an amorphous fluorocarbon polymer that is transparent and has low gas permeability, is spun, cured and then patterned with oxygen plasma on both sides. This hydrophobic layer of Cytop^{TM} repels silicone oil. As a result, when the oil is later dispersed, it will be contained within the patterned Cytop^{TM}-free areas. These areas, which are covered with oil and then Parylene, will define the chambers and actuating membranes. After Cytop^{TM} deposition and patterning, a wafer-through DRIE step connects the front and backside chambers. The silicone liquid is then dispensed and is kept in place on the wafer's surface by the Cytop^{TM} layer. Although the etched-through channels connect the two sides of the wafer, the surface tension at the bottom side, resulting from the effective contact angle modification at the edge of the shallow trench, prevents the liquid from flowing out and provides a way to obtain different initial shapes of the Parylene membranes on the top and bottom sides.

In a single Parylene deposition run, the dielectric liquid is encapsulated on both sides. The Parylene deposition is done while the wafer is flipped over in the deposition chamber, so that the back side faces up. Figure 3 shows the top and bottom view of one of the actuators arrays made using this technique after Parylene deposition over the dispensed liquid. This encapsulation is bubble free since the deposition of the Parylene layer is conformal and done in the vacuum. In the last step, second capacitive electrodes are deposited using an appropriate shadow mask in an e-beam evaporator. For this layer of metal, Cr/Au is again used but the thickness of this second electrode is less than a fifth of that used for the first electrode. This precaution is taken to ensure that the actuating membrane is not too thick nor too rigid.

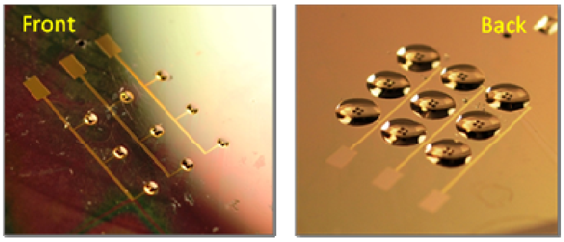

Figure 3: Image of front and back side of the wafer after Parylene deposition but before the second metal layer is deposited. The oil is kept in place during Parylene deposition.

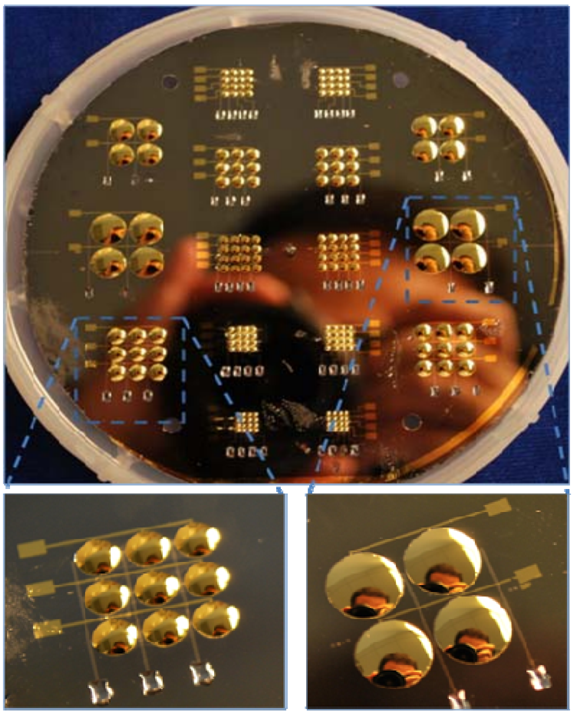

Figure 4: Full wafer view (back side), showing that the introduced fabrication technique can be processed at the wafer level. The high yield of the method also can be observed.

In Figure 4, images of a completed 100-mm wafer with arrays of actuators show that this wafer-level technique has high-yield. One other important feature of this actuator structure is its robustness toward any harsh environmental disturbance (e.g. wind, rain etc.) by which the capacitive gap might be breached or collapsed. In conventional E.S. actuation, the gap is exposed, making the device susceptible to disturbance. In contrast, in the EMA structure the gap is filled with liquid and is encapsulated by the Parylene membranes.

EXPRIMENTAL RESULTS

Table 2 lists measured dimensions of several fabricated devices. By modifying the process, the curvature radius of the back chamber membrane was increased by almost 9x from the first batch of devices (Device 1-2) to the second batch (Device 2-2), for the same membrane radius. This results in a significant improvement in performance of the actuator cells.

Table 2: Dimensions of the fabricated devices along with the measured height of the membranes and calculated curvature radii.

	D_f [μm]	D_b [μm]	h_b [μm]	$R_{C,b}$ [mm]
Dev 1-1	2000	4472	264	9.59
Dev 1-2	1000	2236	163	3.91
Dev 2-1	2000	4472	62.4	37.7
Dev 2-2	1000	2236	19.0	32.8
Dev 2-3	500	1118	7.04	21.0

* D_f and D_b are the diameters of the front and back side chambers, respectively. $R_{C,b}$ and h_b are the curvature radius and height of the back side membrane.

Among all the parameters, the curvature radius of the silicone oil bubble is very important since it strongly influences the electrostatic force generation. For a curved electrode with low curvature radius, a higher voltage is needed to generate the same force compared to an identically sized electrode with a higher curvature radius. In order to achieve higher curvature radius and thus get higher force at lower applied voltage, we made a shallow recess on the backside in the locations of the chambers. This recess has the same pattern as the Cytop^{TM} creating a step at its edge. This step helps to keep the liquid in place. Combined with the hydrophobicity of Cytop^{TM}, less liquid oil is needed to cover the chamber areas, which means the oil bubble's height is lesser and the curvature radius is increased. The recess formation is done prior to Cr/Au deposition. As noted in Table 2, this process significantly increases the curvature radius from 3.91 mm in Device 1-2 to 32.8 mm in Device 2-2.

Deflection of the back side membrane vs. applied voltage is shown in Figures 5 and 6. As the voltage increases, the membrane deflection increases and its shape changes. At 200 V the membrane partially sinks and partially bulges. However, an analysis of the volumetric change proves that despite this, a net volume is transferred to the other side. This volume dislocation results in force transfer from one side to the other. Furthermore, volume transfer was observed for actuation voltages from DC to 15 Hz ac.

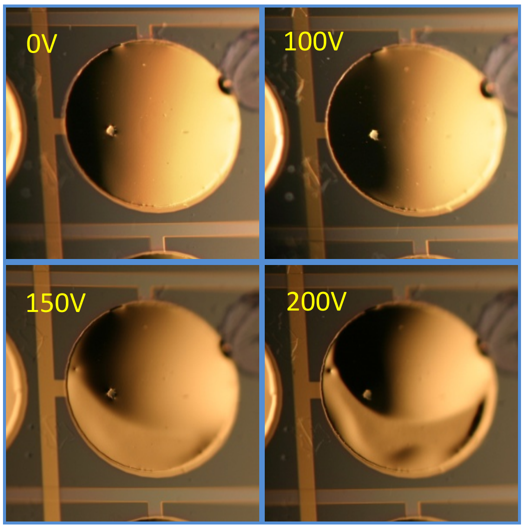

Figure 5: 3-D surface profiles of one of the cells of device 2-2 at 0, 100, 150 and 200 V. The pictures show the gradual deflection of the membrane as the voltage increases.

When 200 V is applied to a curved back side electrode actuator with diameter of 2236 µm, the front side membrane shows 30.0 µm deflection at 14.4 kPa of pressure. This pressure is caused by an 11.3 mN force generated by the capacitive actuator on the back side, where the deflection is much less. On the front side the force is amplified by a factor equal to the area-ratio of the chambers' capacitors. Our process allows flexibility in the size of the chambers and the membrane areas, so that forces in the range of 25-50mN should be achievable.

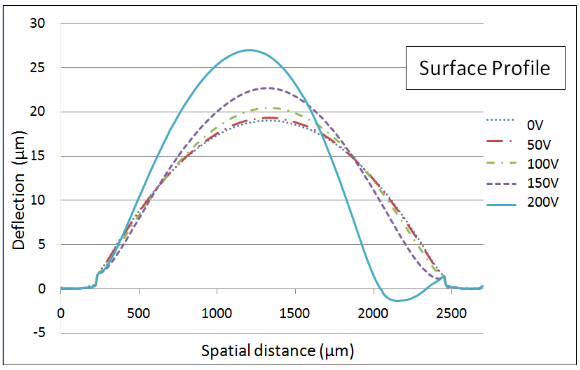

Figure 6: Surface profile of one of the cells (array of devices 2-2) with applied DC voltages of 0V to 200V. The membrane shape changes gradually as the voltage increases. At high voltages, the membrane partially collapses.

In order to compare the EMA technology to other techniques, we calculate the amount of force that can be produced by various capacitive actuators. As shown in Table 3, the normalized force generated by the hybrid EMA structure is almost 30 times larger than that of an air-gap capacitor with the same electrode curvature.

Table 3: Normalized force generated by three capacitive actuators. Dimensions match fabricated devices: membrane radius of 2200 µm, curvature radius of 33 mm, and gap around the edge of the curved electrode of 5.4 µm. The hydraulic amplification factor is assumed to be 10.

	Curved electrode, Air gap	Flat electrode. Air gap	Curved electrode, Liq. gap, Hyd. Amp
Force/ $\varepsilon_0 V^2$	1.92 e4	6.52 e4	5.74 e5

CONCLUSION

We have successfully demonstrated a new type of hybrid actuator that takes advantage of both electrostatic actuation and hydraulic amplification to provide high force and large deflection. With this technique, generation of forces on the order of 50 mN should be achievable with a cell diameter of slightly more than 2 mm. This structure is likely to be used for a variety of applications such valves for fluidic circuits, or as the base structure for motion/flow sensing or actuatable appendages. Moreover, the high-yield, wafer-level fabrication method developed here can be used for other MEMS applications where bubble-free liquid encapsulation is desired.

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